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ON WIND-INDUCED UNDERWATER AMBIENT NOISE.(U)

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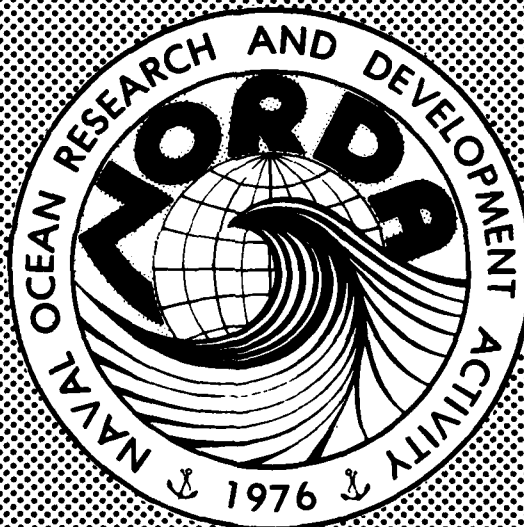
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**NORDA Technical Note 89**

**Naval Ocean Research  
and Development Activity**

NSTL Station, Mississippi 39529

**On Wind-induced  
Underwater Ambient Noise**

AD A101682



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March 1981

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ABSTRACT

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A study of the wind dependence of underwater ambient noise is presented. This study includes a general theory of noise generation, status of available theories, and some recent noise measurements. The general theory indicates that the stresses and the motion of sea-air boundary contribute as a major source of wind-induced noise, and that the boundary conditions play very important roles. Even though several theories have been developed in recent years to investigate specific mechanisms of wind-induced underwater noise, careful evaluations of the theories are suggested. The wind dependence of underwater ambient noise can be identified in the frequency range 1-500 Hz (and higher) from available data. Due to possible interferences of shipping noise, system noise, and flow turbulence near the hydrophone, additional field measurements are necessary to obtain quantitative assessments of wind-induced noise in the frequency range 1-100 Hz. Recommendations are given for future research work on wind-induced noise.

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#### ACKNOWLEDGEMENTS

The author is grateful to Anthony J. Perrone, (Naval Underwater Systems Center, New London, Conn.) and Jack A. Shooter, (Applied Research Laboratories, University of Texas at Austin) for providing unpublished data, to Linda H. McRaney for assistance in preparing the manuscript, and especially to Aubrey L. Anderson for comments and suggestions regarding this article.

## INTRODUCTION

Underwater ambient noise has been measured and investigated intensively for the last forty years. Prior to 1970, comprehensive summaries of various ambient noise studies have been given by Knudsen et al. [42]\* and by Wenz [109,110]. In general, the underwater ambient noise can be identified with three main sources: water motion, biological activities, and manmade sources. According to Wenz [110] some general features of ambient noise spectra are shown in Fig. 1. In the frequency band 1 to 10 or 20 Hz, a steep negative slope of -8 to -10 dB/Oct is frequently observed. It is suggested that the source of this noise is large-scale oceanic turbulence. From about 500 Hz to 25 Hz, the usual slope is at -5 to -6 dB/Oct. The source of this noise is in the agitation of all the sea surface, and the noise levels correlate well with wind speed and waveheight. In the band 10-500 Hz, the spectrum is highly variable. There is evidence that a major source of this component is ship traffic.

The wind dependence of underwater ambient noise has recently received considerable attention, especially in the low frequencies (1-500 Hz) [21, 115, 116, 119]. In this paper, a general theory of noise generation is presented in section I. In section II a brief description is given of the status of available theories of wind-induced underwater noise. Outlines of some recent noise measurements are stated in section III, and concluding remarks are presented in section IV. Detailed studies will be presented in separate papers.

### I. GENERAL THEORY

#### A. GENERAL DIFFERENTIAL EQUATION

A general differential equation for noise generation can be derived from the continuity and momentum equations of fluid mechanics for regions that include mass and force sources. Using tensor notation, the continuity and momentum equations can be written in the forms

$$\frac{\partial \rho}{\partial t} + \frac{\partial}{\partial x_i}(\rho v_i) = q \quad (1)$$

$$\frac{\partial \rho v_i}{\partial t} + \frac{\partial}{\partial x_j}(\rho v_i v_j + p_{ij}) = F_i \quad (2)$$

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\* References are not given in numerical order; they are part of the Bibliography section at the end of the text.

where  $\rho$  = density,  $t$  = time,  $v_i$  = component of velocity in direction  $x_i$  ( $i = 1, 2, 3$ ),  $q$  = mass source,  $p_{ij}$  = compressive stress tensor, and  $F_i$  = external force component.

By eliminating  $\rho v_i$  between the two equations, it is found that

$$\frac{\partial^2 \rho}{\partial t^2} = \frac{\partial^2}{\partial x_i \partial x_j} (\rho v_i v_j + p_{ij}) + \frac{\partial q}{\partial t} - \frac{\partial F_i}{\partial x_i} \quad (3)$$

subtracting

$$c_0^2 \frac{\partial^2 \rho}{\partial x_i^2} = \delta_{ij} c_0^2 \frac{\partial^2 \rho}{\partial x_i \partial x_j} = \frac{\partial^2 (c_0^2 \rho \delta_{ij})}{\partial x_i \partial x_j}$$

from both sides of Equation 3, we have

$$\frac{\partial^2 \rho}{\partial t^2} - c_0^2 \frac{\partial^2 \rho}{\partial x_i^2} = G(x_i, t) \quad (4)$$

where

$c_0$  = Speed of Sound

$$T_{ij} = \rho v_i v_j + p_{ij} - c_0^2 \rho \delta_{ij}$$

$$G = \frac{\partial q}{\partial t} - \frac{\partial F_i}{\partial x_i} + \frac{\partial T_{ij}}{\partial x_i \partial x_j}$$

Equation 4 is the general differential equation for noise generation, and it is equivalent to the similar equation given by Ross [91].

## B. SOLUTION

Equation 4 is an inhomogeneous wave equation, and the general solution is known as [20]

$$\begin{aligned} \rho - \rho_0 = & \frac{1}{4\pi c_0^2} \int_V \frac{[G]}{r} dV(\vec{y}) \\ & + \frac{1}{4\pi} \int_S \left\{ \frac{1}{r} \left[ \frac{\partial \rho}{\partial n} \right] - \frac{\partial}{\partial n} \left( \frac{1}{r} \right) [\rho] + \frac{1}{c_0 r} \frac{\partial r}{\partial n} \left[ \frac{\partial \rho}{\partial t} \right] \right\} dS(\vec{y}) \end{aligned} \quad (5)$$

in which the symbol

$$[G] = G(\vec{y}, t - \frac{r}{c_0})$$

denotes a function with retarded time, where  $r = |\vec{x} - \vec{y}|$ , and  $\vec{n}$  is the outward normal from the fluid. The first integral is taken over the volume  $V$  external to the boundaries, and the second integral is taken over the surface of the volume  $V$ .

By applying the divergence theorem, we have

$$\int_V \left[ \frac{\partial F_i}{\partial y_i} \right] \frac{dV(\vec{y})}{r} - \frac{\partial}{\partial x_i} \int_V \left[ F_i \right] \frac{dV(\vec{y})}{r} = \int_V \frac{\partial}{\partial y_i} \left[ \frac{F_i}{r} \right] dV(\vec{y}) = \int_S \ell_i [F_i] \frac{dS(\vec{y})}{r} \quad (6)$$

where  $\ell_i$  are the direction cosines of the outward normal from the fluid.

Similarly we have

$$\int_V \left[ \frac{\partial T_{ij}}{\partial y_i \partial y_j} \right] \frac{dV(\vec{y})}{r} - \frac{\partial}{\partial x_i} \int_V \left[ \frac{\partial T_{ij}}{\partial y_j} \right] \frac{dV(\vec{y})}{r} = \int_S \ell_i \left[ \frac{\partial T_{ij}}{\partial y_j} \right] \frac{dS(\vec{y})}{r} \quad (7)$$

By repeating this a second time, we obtain

$$\int_V \left[ \frac{\partial T_{ij}}{\partial y_j} \right] \frac{dV(\vec{y})}{r} - \frac{\partial}{\partial x_j} \int_V \left[ T_{ij} \right] \frac{dV(\vec{y})}{r} = \int_S \ell_j [T_{ij}] \frac{dS(\vec{y})}{r} \quad (8)$$

From (6), (7) and (8), we have

$$\begin{aligned} \int_V \left[ \frac{G}{r} \right] dV(\vec{y}) &= \int_V \left[ \frac{\partial q}{\partial t} \right] \frac{dV(\vec{y})}{r} - \int_V \left[ \frac{\partial F_i}{\partial y_i} \right] \frac{dV(\vec{y})}{r} + \int_V \left[ \frac{\partial T_{ij}}{\partial y_i \partial y_j} \right] \frac{dV(\vec{y})}{r} \\ &= \int_V \left[ \frac{\partial q}{\partial t} \right] \frac{dV(\vec{y})}{r} - \frac{\partial}{\partial x_i} \int_V \left[ F_i \right] \frac{dV(\vec{y})}{r} + \frac{\partial^2}{\partial x_i \partial x_j} \int_V \left[ T_{ij} \right] \frac{dV(\vec{y})}{r} \\ &\quad - \int_S \ell_i [F_i] \frac{dS(\vec{y})}{r} + \frac{\partial}{\partial x_i} \int_S \ell_j [T_{ij}] \frac{dS(\vec{y})}{r} + \int_S \ell_i \left[ \frac{\partial T_{ij}}{\partial y_j} \right] \frac{dS(\vec{y})}{r} \end{aligned} \quad (9)$$

The surface integral which appears in Eq. 5 can be transformed into the different form, we have

$$\begin{aligned} \int_S \left\{ \frac{1}{r} \left[ \frac{\partial \rho}{\partial n} \right] - \frac{\partial}{\partial n} \left( \frac{1}{r} \right) [\rho] + \frac{1}{c_{or}} \frac{\partial r}{\partial n} \left[ \frac{\partial \rho}{\partial t} \right] \right\} dS(\vec{y}) \\ = \int_S \ell_i \left\{ \frac{1}{r} \left[ \frac{\partial \rho}{\partial y_i} \right] + \frac{1}{r^2} \frac{\partial r}{\partial y_i} [\rho] + \frac{1}{c_{or}} \frac{\partial r}{\partial y_i} \left[ \frac{\partial \rho}{\partial t} \right] \right\} dS(\vec{y}) \\ = \int_S \ell_i \frac{1}{r} \frac{\partial}{\partial y_j} [\rho \delta_{ij}] dS(\vec{y}) - \int_S \ell_i \frac{\partial r}{\partial x_i} \left( \frac{1}{r^2} [\rho] + \frac{1}{c_{or}} \left[ \frac{\partial \rho}{\partial t} \right] \right) dS(\vec{y}) \\ = \int_S \ell_i \frac{1}{r} \frac{\partial}{\partial y_j} [\rho \delta_{ij}] dS(\vec{y}) + \int_S \ell_j \frac{\partial}{\partial x_i} \left( \frac{1}{r} [\rho \delta_{ij}] \right) dS(\vec{y}) \end{aligned} \quad (10)$$

Substituting from (9) and (10) into (5) we obtain

$$\begin{aligned}
 \rho - \rho_0 = & \frac{1}{4\pi c_0^2} \int_V \left[ \frac{\partial q}{\partial t} \right] \frac{dV(\vec{y})}{r} \\
 & - \frac{1}{4\pi c_0^2} \frac{\partial}{\partial x_i} \int_V [F_i] \frac{dV(\vec{y})}{r} \\
 & + \frac{1}{4\pi c_0^2} \frac{\partial^2}{\partial x_i \partial x_j} \int_V [T_{ij}] \frac{dV(\vec{y})}{r} \\
 & - \frac{1}{4\pi c_0^2} \int_S \ell_i [F_i] \frac{dS(\vec{y})}{r} \\
 & + \frac{1}{4\pi c_0^2} \int_S \ell_i \frac{\partial}{\partial y_j} [T_{ij} + c_0^2 \rho \delta_{ij}] \frac{dS(\vec{y})}{r} \\
 & + \frac{1}{4\pi c_0^2} \frac{\partial}{\partial x_i} \int_S \ell_j [T_{ij} + c_0^2 \rho \delta_{ij}] \frac{dS(\vec{y})}{r}
 \end{aligned} \tag{11}$$

By substituting for  $T_{ij} = \rho v_i v_j + p_{ij} - c_0^2 \rho \delta_{ij}$ , Equation 11 can be written in the form

$$\begin{aligned}
 \rho - \rho_0 = & \frac{1}{4\pi c_0^2} \int_V \left[ \frac{\partial q}{\partial t} \right] \frac{dV(\vec{y})}{r} \\
 & - \frac{1}{4\pi c_0^2} \frac{\partial}{\partial x_i} \int_V [F_i] \frac{dV(\vec{y})}{r} \\
 & + \frac{1}{4\pi c_0^2} \frac{\partial^2}{\partial x_i \partial x_j} \int_V [T_{ij}] \frac{dV(\vec{y})}{r} \\
 & + \frac{1}{4\pi c_0^2} \int_S \ell_i \left[ \frac{\partial}{\partial y_j} (\rho v_i v_j + p_{ij}) - F_i \right] \frac{dS(\vec{y})}{r} \\
 & + \frac{1}{4\pi c_0^2} \frac{\partial}{\partial x_i} \int_S \ell_j [\rho v_i v_j + p_{ij}] \frac{dS(\vec{y})}{r}
 \end{aligned} \tag{12}$$



By utilizing (2), we have

$$\begin{aligned}
 \rho - \rho_0 = & \frac{1}{4\pi c_0^2} \int_V \left[ \frac{\partial q}{\partial t} \right] \frac{dV(\vec{y})}{r} \\
 & - \frac{1}{4\pi c_0^2} \frac{\partial}{\partial x_i} \int_V [F_i] \frac{dV(\vec{y})}{r} \\
 & + \frac{1}{4\pi c_0^2} \frac{\partial}{\partial x_i \partial x_j} \int_V [T_{ij}] \frac{dV(\vec{y})}{r} \\
 & - \frac{1}{4\pi c_0^2} \int_S \ell_i \left[ \frac{\partial \rho v_i}{\partial t} \right] \frac{dS(\vec{y})}{r} \\
 & + \frac{1}{4\pi c_0^2} \frac{\partial}{\partial x_i} \int_S \ell_j [\rho v_i v_j + p_{ij}] \frac{dS(\vec{y})}{r}
 \end{aligned} \tag{13}$$

Equation 13 is more general than the solutions given in the literature. For example, if we drop the sources terms and choose specific boundary conditions, we can reduce Equation 13 to the result of Powell [87]. Furthermore, if there is zero velocity and the solid boundaries, we have the result of Curle [20]. If the boundary effect is neglected, we have the result of Lighthill [57,58].

### C. INTERPRETATION

The five terms on the right of Equation 13 represent the various sources of noise generation.

1. The first term on the right involves the rate of mass source,  $q$ . However, if we consider Equation 1 as the continuity equation of the fluid mixture, the mass source should equal to zero.

2. The second term, the external force acting on the volume, is of dipole nature. The importance of this term depends on the nature of the force and the scales of time and space.

3. The third term, involving the turbulent stresses ( $T_{ij}$ ) and the compressible stresses ( $P_{ij}$ ) in the fluid volume, is the term which Lighthill derived and showed to be of quadrupole nature.

4. The fourth term, involving the motion of the boundary, acts as a monopole.
5. The fifth term, involving the turbulent stresses and the compressible stresses acting on the boundary, is of dipole nature.

For the problems of wind-induced underwater ambient noise, the last two terms are of the most importance. The stresses and the motion of sea-air boundary contribute the major sources of wind-induced underwater noise. However, the dynamics and the interactions of the sea-air interface are very complicated, involving wave motions, instabilities, breaking, impacts, bubbles, currents and turbulence.

## II. STATUS OF THEORIES

Several theories have been proposed to relate the underwater ambient noise with surface winds. The proposed noise generating mechanisms can be divided into four groups. The first group [38,115] considers that wind turbulence is a source of the underwater ambient noise. The second [9,31,36,47,60,68] deals with the interactions of ocean surface waves. The third group [28] treats the interaction of surface waves with oceanic turbulence. The fourth [109,116] considers the spray and bubbles to be sources of ambient-noise. A comprehensive investigation of the first three mechanisms has been given by Yen and Perrone [119]. Their study mainly concerns itself with the wind-generated noise spectrum below 10 Hz. When considering only the low frequency noise, the formulation can be simplified. The statistical nature of ambient noise is emphasized instead of deriving a deterministic model.

### A. WIND TURBULENCE

The fluctuations of wind turbulence would generate underwater ambient noise due to the wind action on the sea-air interface. The mechanisms of sea-air interaction are very complex even though considerable advancements have been made in the recent years [14,50,59,65,72,85,90,95,96,98,117]. The role of wind turbulence in the generation of underwater ambient noise has received limited study. Recently, Wilson [115] extends the development of the theory of turbulent pressure fluctuation initiated by Isakovick and Kur'yanov [38]. The theory of Isakovick and Kur'yanov is based on the model of noise generated directly by the forces of the wind on the water, i.e., on the same mechanism as that which produces ocean surface waves. For low-frequency sound waves where the wavelength is much greater than the height of the surface wave, the sea surface is considered as a horizontal plane. It is shown that the spectral density of the underwater sound field is related to the space-time spectral density of the wind turbulent pressure fluctuations on the surface of water. Since there are no direct measurements of the wind turbulent pressure fluctuations on the sea surface, it is necessary to use indirect data for the flow past solid boundaries with various degrees of roughness. This gives a basis for the assumption that for wind flow over the ocean, roughness is dictated by the surface wave of the ocean. Thus the spectral density of the underwater noise can be determined indirectly by relating it to the sea surface spectrum which has been measured by different researchers. Due to the different methods of calculation, the results of Wilson are significantly different from that of Isakovick and Kur'yanov. In the frequency band 5 to 50 Hz, Wilson showed that the wind speed and frequency dependence of the calculated source spectrum level agrees well with data measured in the northeastern Pacific Ocean under low shipping noise conditions.

### B. SURFACE WAVE INTERACTION

The noise-generating mechanisms of surface wave interactions have been studied by several investigators. It is known that the pressure fluctuations, which are

caused by the linearized surface waves, penetrate into the water up to a distance of the order of a wavelength. However, Longuet-Higgins [60] showed that the interaction of two surface waves would form pressure fluctuations which do not decrease with depth. Based on a model of quadratic interactions of oppositely traveling surface waves, and incorporating several surface wave spectral models, Hughes [36] estimated noise spectral level for the range 1-3000 Hz. In comparison with the measurements of Perrone [80], it is shown that reasonable agreement with measurements exists for frequencies less than 10 Hz; however, the wrong spectral shape is shown at higher frequencies.

### C. SURFACE WAVES AND OCEANIC TURBULENCE INTERACTION

Noise generation by the interaction of surface waves and oceanic turbulence has been studied by Goncharov [28]. The motion of water particles in the surface layer of the ocean is affected by surface waves, but also by oceanic turbulence. Since particle speed is much greater in a surface wave than it is in turbulent motion, it might appear that the surface wave interaction is the only important mechanism. However, the noise radiated by surface wave interaction is a second order quantity, so the noise radiated by the interaction of surface waves and oceanic turbulence may be important for certain frequencies. Under certain assumptions concerning the properties of the turbulence, Goncharov showed that the estimated source spectrum levels are in reasonable agreement with experimental data at 10 Hz and 100 Hz.

### D. SPRAY AND BUBBLES

Wenz [109,110] suggested that in the band 50 Hz to 20K Hz, the ambient noise is mainly wind-dependent noise from bubbles and spray. Recently the noise source spectrum levels for the impact of spray have been investigated by Wilson [116] in the band 50 to 1000 Hz. An empirical approach was used based on the recent measurement of white capping index as a function of wind speed, the noise measurements of Morris [74], and the impact results of Franz [24].

## III. RECENT DATA OF AMBIENT NOISE

By studying several recently gathered data sets of underwater ambient noise, it was found that the ambient noise spectra vary, depending on location, time, frequency, hydrophone depth, and wind speed. Some representative results are given in the following:

### A. LOCATION

The typical noise spectra [41] for Sites A and C are shown in Figure 2. Both Sites A and C were located in the eastern North Pacific Center Water areas. In comparison with a noise spectrum of the South Pacific Ocean, Figure 3 clearly indicates the influence of more shipping activity in the Northeast Pacific. The characteristics of a shipping component are shown in Figure 3, and a contribution from whales is also apparent in the North Pacific spectrum.

### B. HYDROPHONE DEPTH AND WIND SPEED

A comparison of noise spectrum level by Shooter at two hydrophone depths, 3572 m and 4572 m, with wind speed is shown in Figure 4. At 224 Hz, the dependence of the noise spectrum on wind speed and hydrophone depth is obvious. Ambient noise levels were measured by Morris [74] at two deep water sites in northeastern Pacific Ocean that were separated by about 1000 miles. Analyses of the data indicate that at frequencies less than 100 Hz the noise level decreases with increasing depth. These low-frequency noise levels are independent of the wind speed. At frequencies 100 Hz

and above, noise levels and the depth dependence of noise are controlled by the wind-induced noise.

#### C. FREQUENCY AND WIND SPEED

The variation of the ambient noise level over a 30-day period and the corresponding variation in wind speeds are presented graphically in Figure 5 in the frequency range 11-2816 Hz. Three qualitative conclusions based on Figure 5 have been drawn by Perrone [80]: (1) The ambient-noise-level curves bearing a striking resemblance to the wind-speed curves in the 141-2816 Hz bands indicate a strong wind dependence in the upper bands. (2) Very little wind dependence is apparent in the 17-112 Hz bands, except at very high wind velocities. (3) In the two lowest frequency bands (center frequencies at 11 Hz and 14 Hz), wind dependence may be obtained. A more recent analysis of the same ambient noise data by Perrone in the frequency range 0.6-12 Hz is shown in Figure 6. Based on Figure 6, the following conclusion can be drawn: (1) The wind dependence can be observed in the 2-12 Hz bands. (2) Little wind dependence is apparent in the 0.6 Hz band due to the limitation of system noise.

#### D. ONE-YEAR AMBIENT NOISE MEASUREMENTS NEAR BERMUDA

The data presented in the open literature by Perrone [80] were obtained during January 1966 from a single omnidirectional hydrophone located near Bermuda at a 4400 m depth. Much more information can be obtained from a NUSC Technical Report [83]. In that report, the results of ambient noise data recorded simultaneously during a one-year period between January and December 1966 from five hydrophones located near Bermuda at depths of 30, 400, 1100, 2400 and 2500 fm (55, 730, 2000, 4400 and 4500 m) are presented. The locations of hydrophones and wind-speed sensors are shown in Figures 7 and 8. The data in Figure 9 are the yearly summary of ambient noise spectra for eight 5-knot wind speed groups and for each of the five hydrophone depths. In the same figure, the histograms illustrating the total number of a 2 minute ambient noise sample contained in the yearly spectra are also given. The ambient noise spectra display variation as a function of wind speed and hydrophone depth. The wind dependence is apparent in the yearly summary of ambient noise spectra even for the deepest hydrophones.

#### IV. CONCLUDING REMARKS

Based on this study of wind-induced underwater ambient noise, the following qualitative remarks can be made.

##### A. FREQUENCY RANGE OF WIND DEPENDENCE

Wind dependence of underwater ambient noise can be observed in the frequency range 1-500 Hz (and higher) in available data. Due to possible interferences of shipping noise, system noise, and flow turbulence near the hydrophone, additional field measurements are necessary to obtain quantitative assessments of wind-induced noise in the frequency range 1-100 Hz. It is especially necessary that environmental data, such as winds, waves, and currents, be recorded simultaneously with the noise data.

##### B. LOCATION AND HYDROPHONE DEPTH

Wind-induced underwater noise is expected to vary with location and hydrophone depth. From the theory of noise generation, Equation 13 indicates that the boundary conditions play very important roles in underwater noise generation. The direct roles are the prescribed external conditions and the reflection of noise.

Furthermore, the boundary conditions affect surface waves, currents and oceanic turbulence, and those quantities contribute to the ambient noise as indicated in Equation 13. Due to the boundary effects, the measurements near Bermuda may not be typical of wind-induced noise in the open ocean. Additional long-term measurements at different typical locations would be useful for the investigation of underwater ambient noise.

### C. THEORY AND MEASUREMENT

Mechanisms of wind-induced underwater ambient noise can be expressed mathematically in the form of Equation 13. As mentioned, the boundary conditions play important roles for underwater noise generation. The stresses and motion of the sea-air boundary contribute the major sources of wind-induced noise. However, calculations or estimations of the right hand side of Equation 13 are very difficult because the mechanisms of the interactions of the sea-air interface are very complex. Even though several theories have been developed in recent years to investigate specific mechanisms of wind-induced underwater noise, careful evaluations of the existing theories are necessary for the following reasons. First, the range of validity is limited for a specific theory due to simplifying assumptions of the derivation. Second, most theories rely on the knowledges of waves and turbulence; however, knowledge of the statistical properties of turbulence and waves in sea-air interaction regions is lacking, particularly in the frequency range 1-500 Hz. Third, there are very few ideal noise measurements for the evaluation of theories, and the results of data analyses may depend on the techniques of data processing.

### D. RECOMMENDATIONS

1. Detailed evaluation of available data of wind-induced underwater ambient noise should be carried out in the frequency range 1-500 Hz.
2. Comparison of various theories of wind-induced underwater noise should be carried out in the frequency range 1-500 Hz.
3. Data analyses should be extended to cover the available data in frequency range from 1 to 100 Hz. In order to evaluate the possible effect of data processing, it is recommended that two independent methods of data processing will be used to analyze a selected data set.
4. Mechanisms of wind-induced noise should be investigated in conjunction with the current research work of sea-air interactions, ocean dynamics and turbulence. Nonlinear interactions and instabilities should be emphasized.
5. Whenever possible, future underwater noise experiments should include such environmental data as wind speeds, waves, and currents.
6. Designed experiments should be carried out for various typical locations, such as deep open ocean, with and without ridges. Continuous measurements of one year are desirable to investigate the statistical properties and the variation of ambient noise with time.

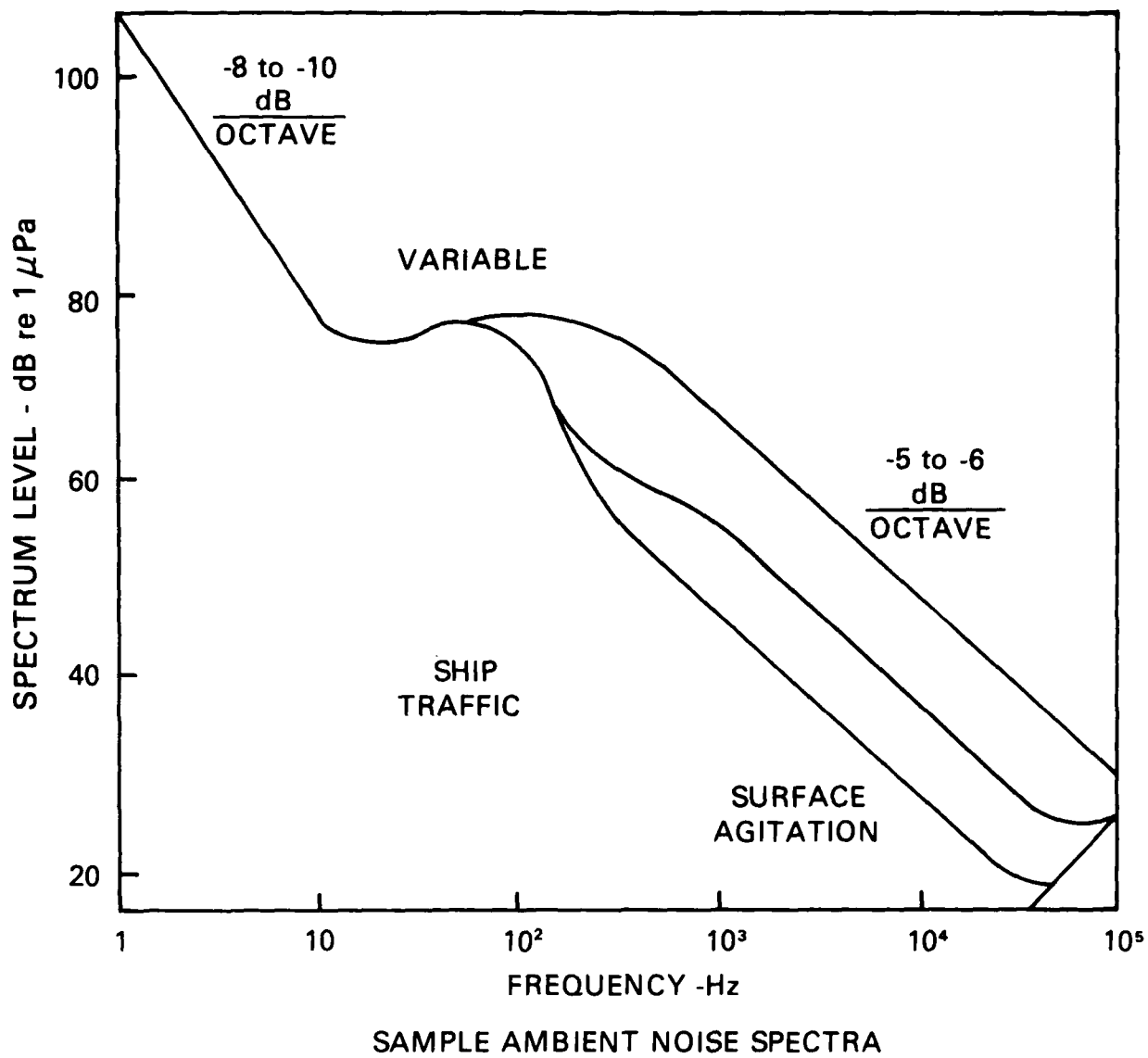


Figure 1. General characteristics of underwater ambient noise spectra (Wenz, 1972)

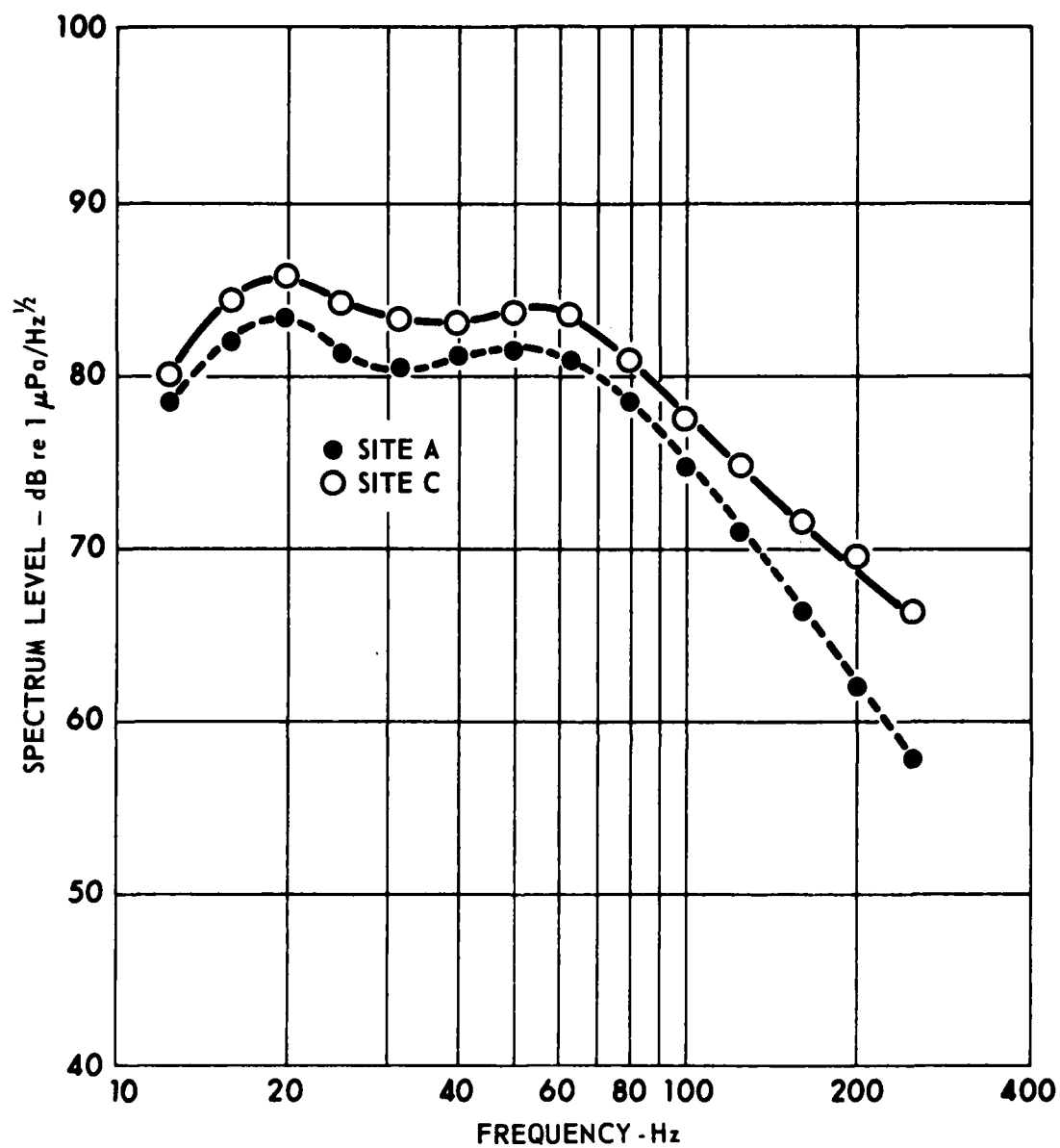


Figure 2. Comparison of noise levels at five sites in the North Pacific (Kibblewhite, Shooter, and Watkins, 1976)

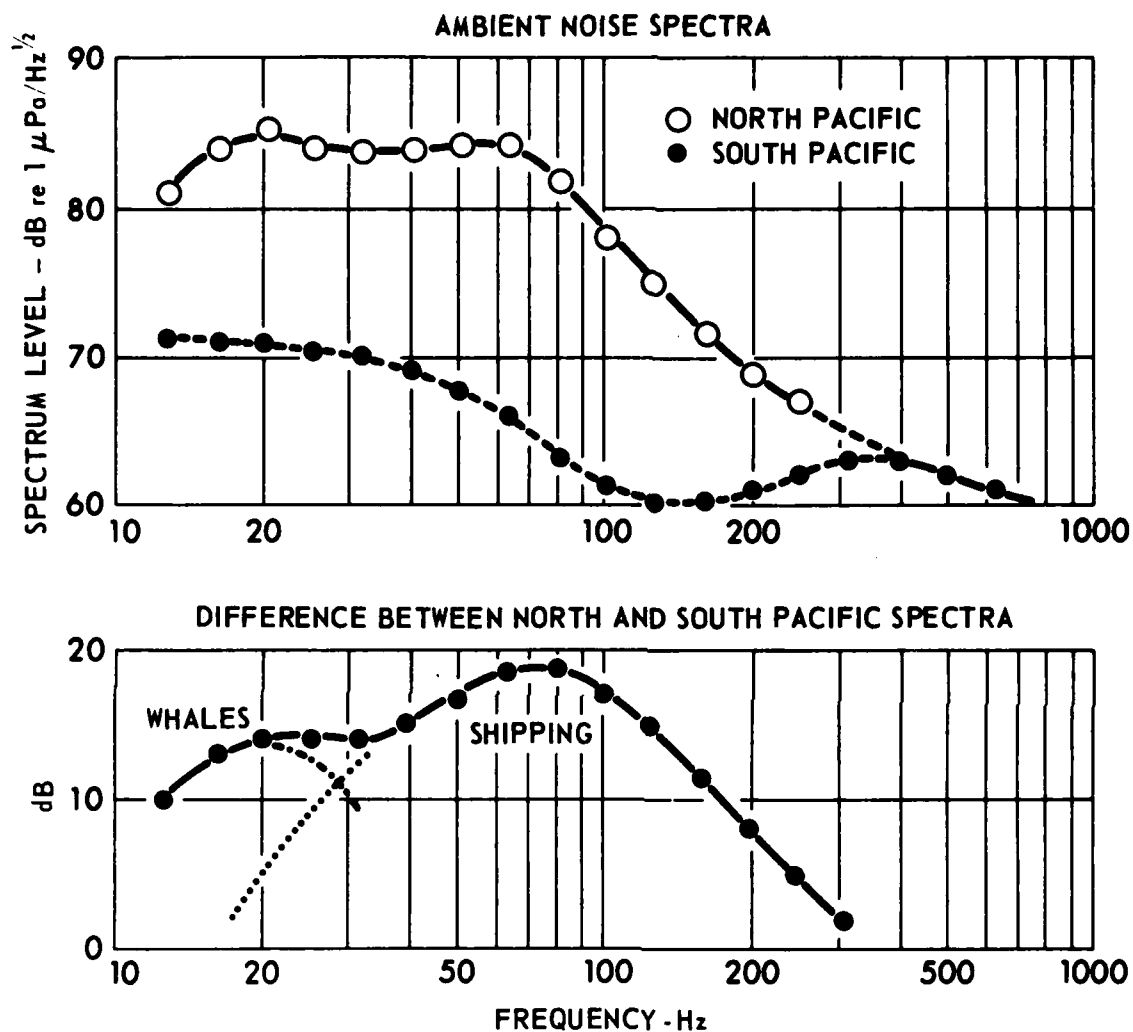


Figure 3. Comparison of North and South Pacific ambient noise spectra (Kibblewhite, Shooter, and Watkins, 1976)



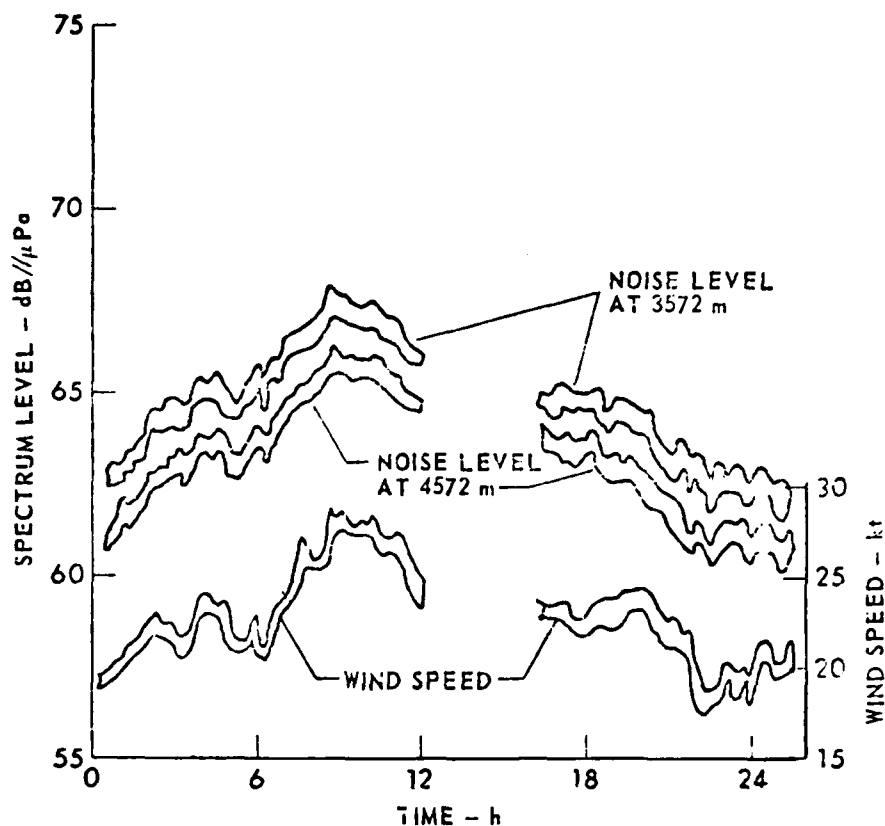


Figure 4. Comparison of noise level (at 224 Hz) at 3572 m and 4572 m with wind speed (Unpublished data of Shooter at ARL, University of Texas at Austin. Used by permission.)

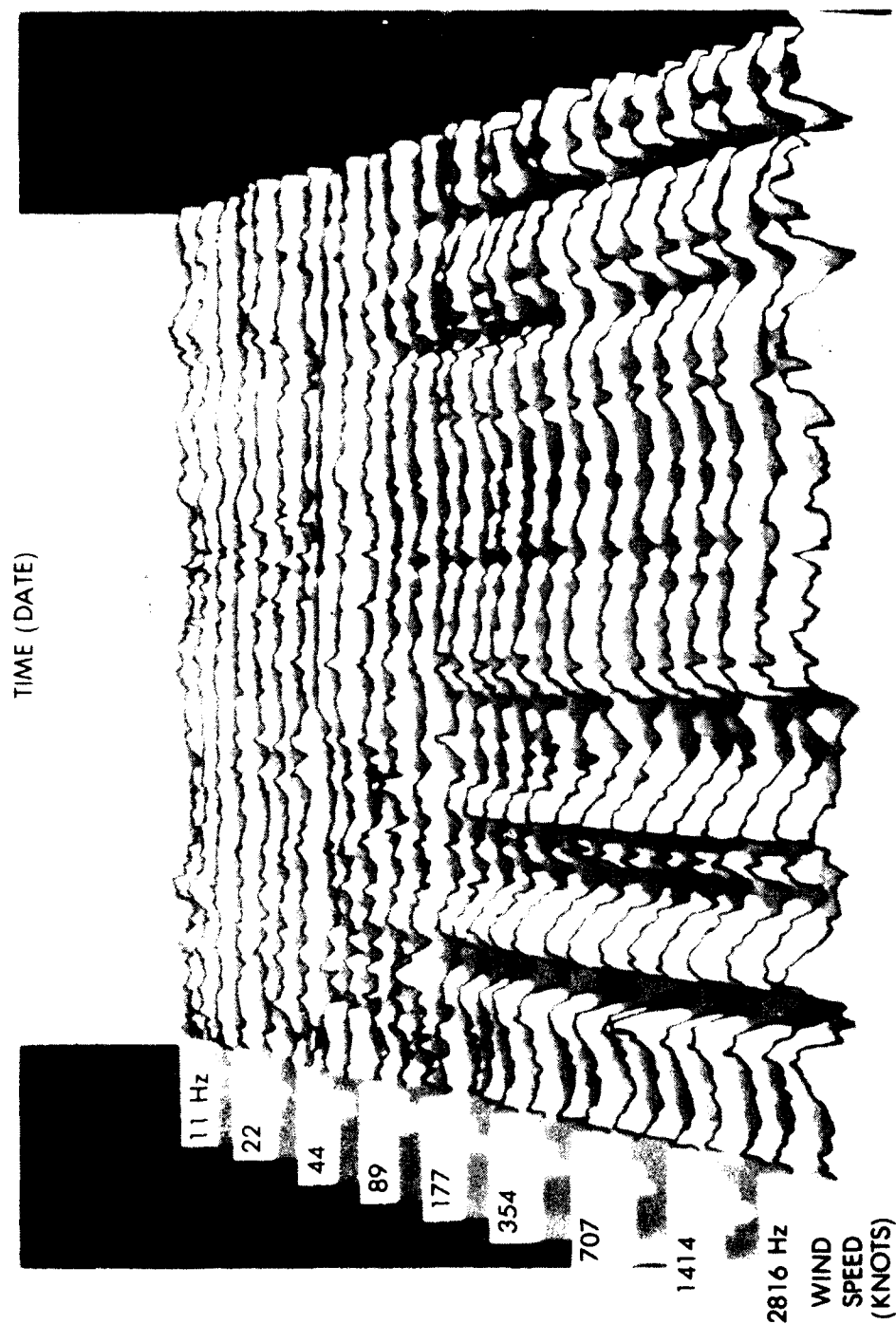


Figure 5. Variations in ambient noise levels and wind speed with time in 11-2816 Hz range (Perrone, 1969)

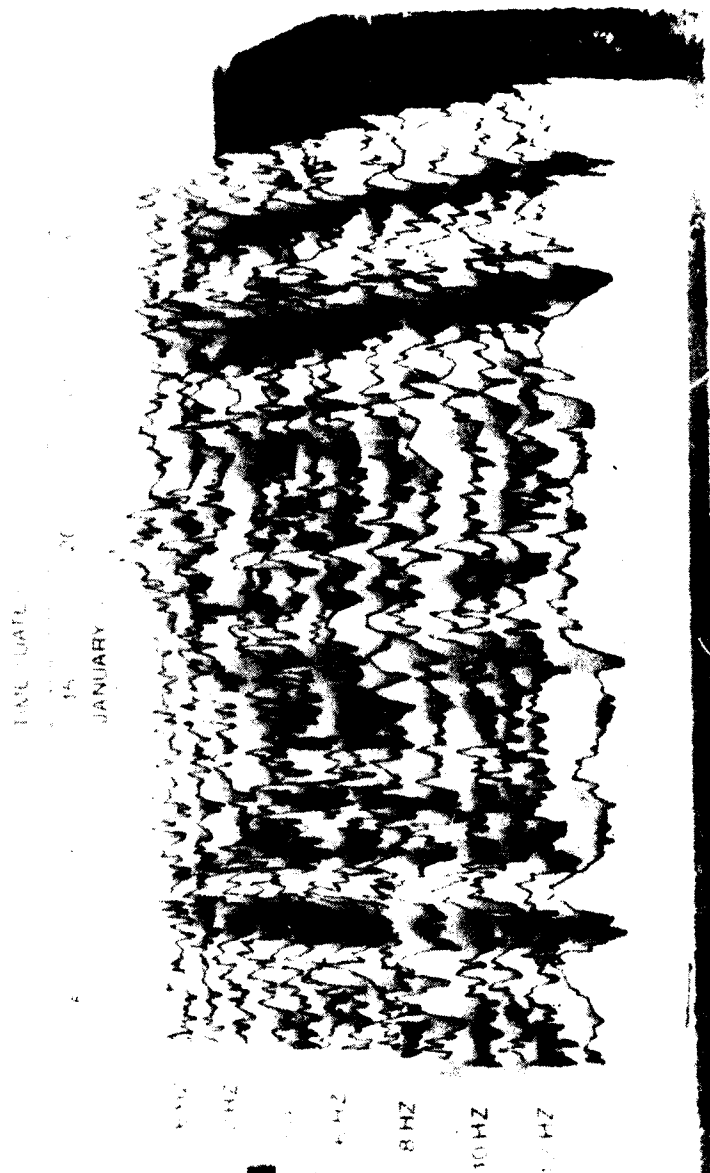


Figure 6. Variation in ambient noise levels and wind speed with time in 0.6-12.0 Hz range (Unpublished data of Perrone at the Naval Underwater Systems Center, New London. Used by permission.)

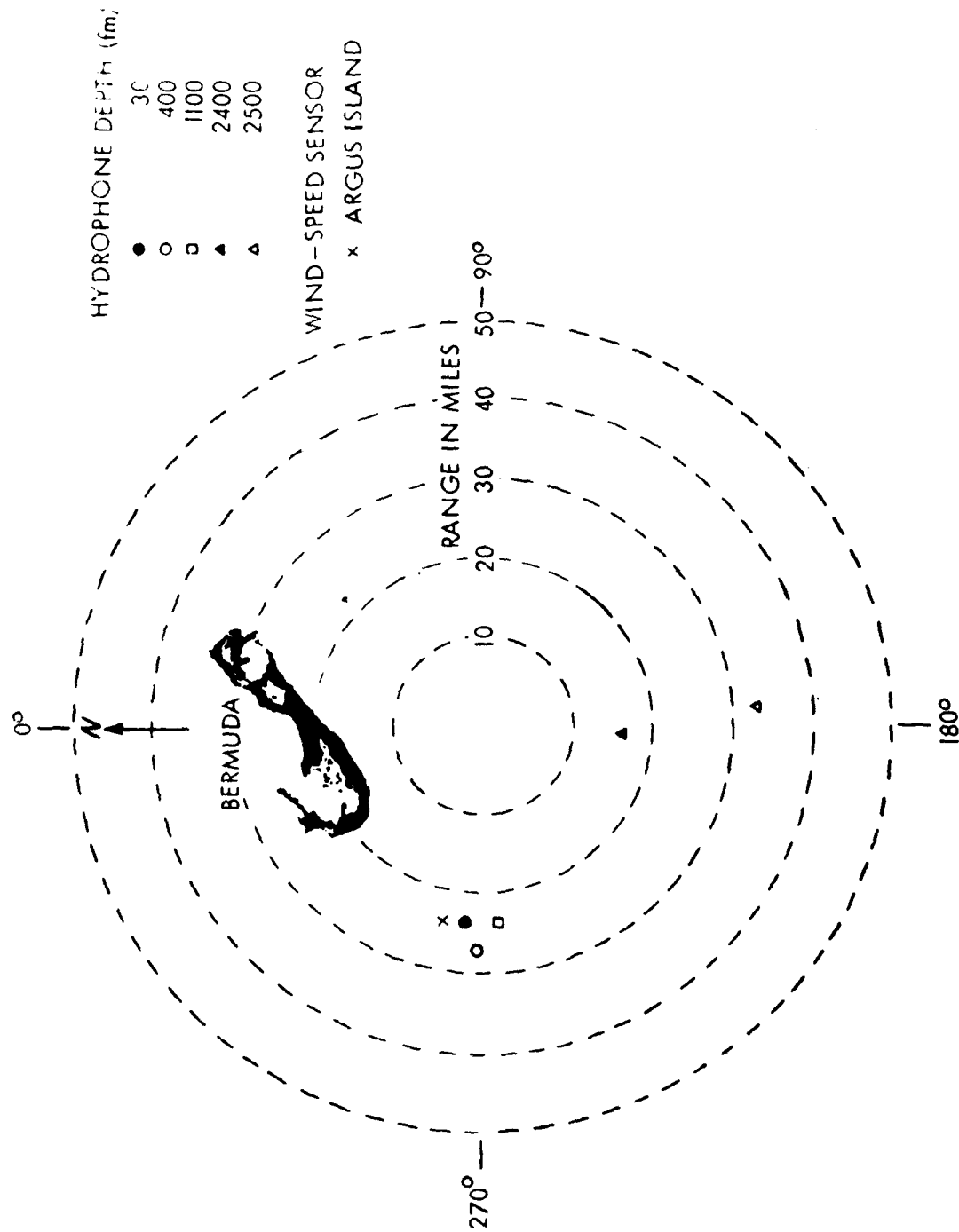


Figure 7. Hydrophone and wind speed sensor locations (Perrone, 1976)

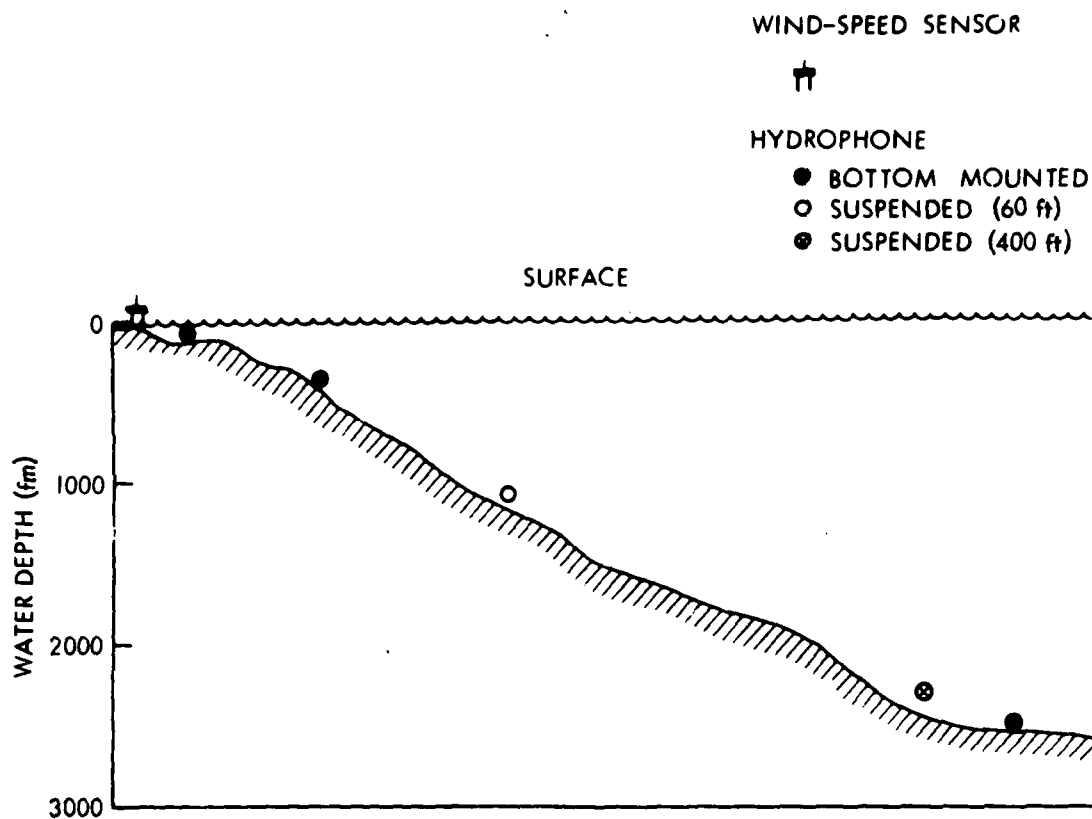
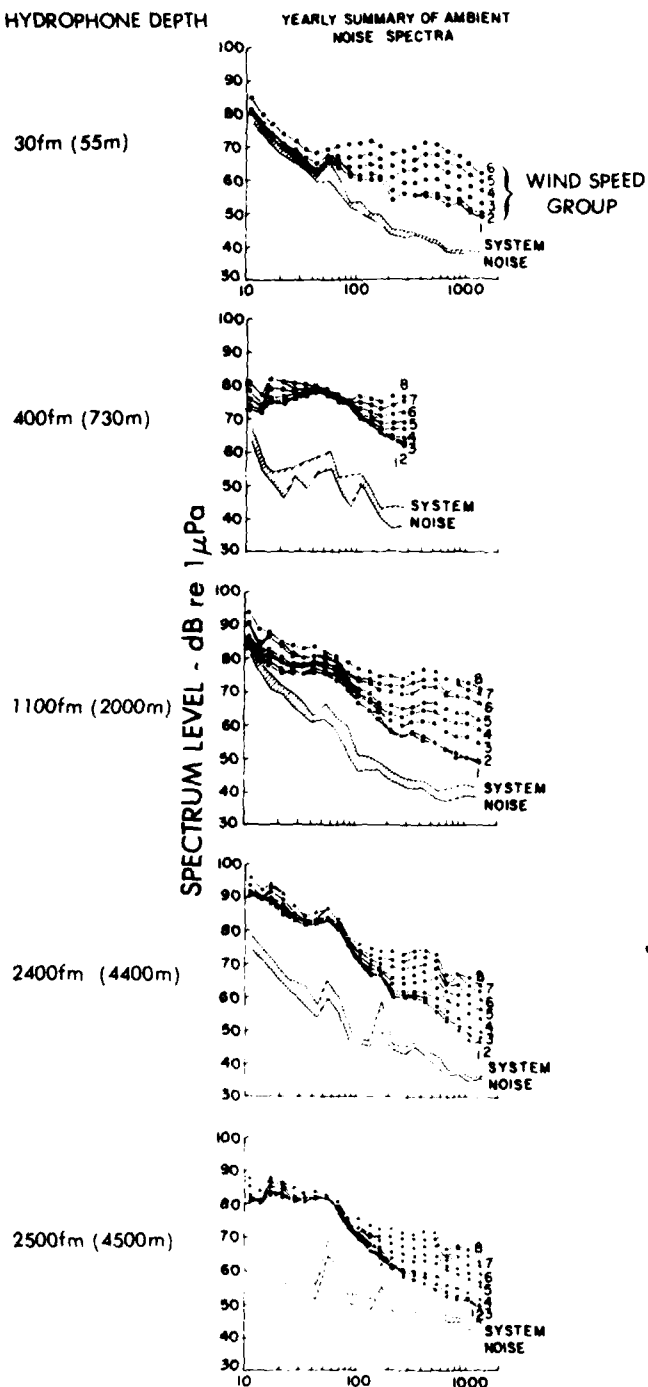


Figure 8. Hydrophone depths (Perrone, 1976)

# HYDROPHONE DEPTH



# YEARLY SUMMARY AND NUMBER OF NOISE SAMPLES FOR EACH WIND SPEED GROUP

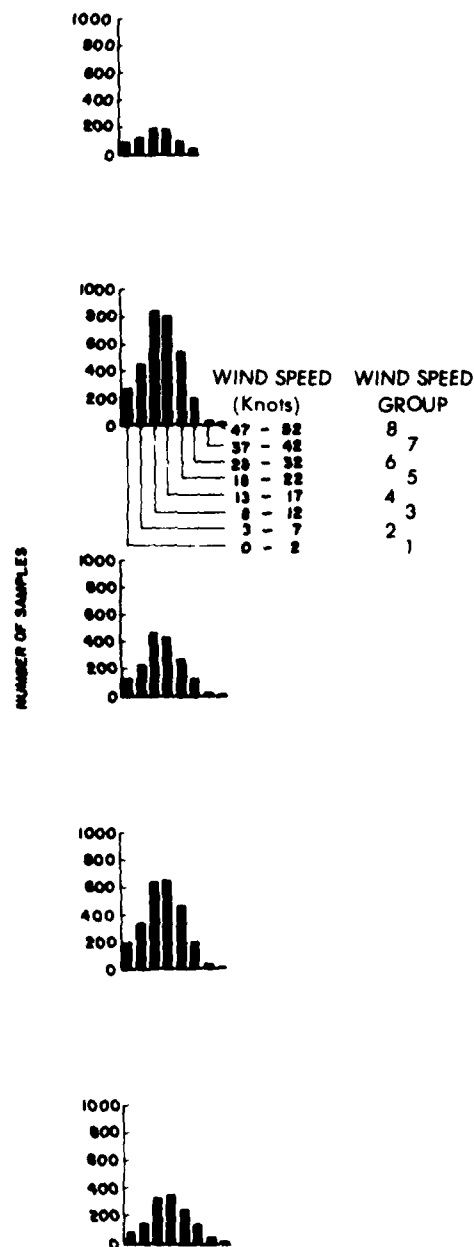


Figure 9. Yearly summary of ambient noise measurement program off Bermuda (Perrone, 1976)

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1. REPORT NUMBER NORDA Technical Note 89	2. GOVT ACCESSION NO. AD-A101682	3. RECIPIENT'S CATALOG NUMBER
4. TITLE (and Subtitle) On Wind-induced Underwater Ambient Noise		5. TYPE OF REPORT & PERIOD COVERED 97
7. AUTHOR(s) Huo, Li		6. PERFORMING ORG. REPORT NUMBER
9. PERFORMING ORGANIZATION NAME AND ADDRESS Naval Ocean Research & Development Activity Ocean Science & Technology Laboratories, Code 320 NSTL Station, Mississippi 39529		8. CONTRACT OR GRANT NUMBER(s)
11. CONTROLLING OFFICE NAME AND ADDRESS Same		10. PROGRAM ELEMENT, PROJECT, TASK AREA & WORK UNIT NUMBERS 105
14. MONITORING AGENCY NAME & ADDRESS (if different from Controlling Office)		12. REPORT DATE March 1981
		13. NUMBER OF PAGES 26
		15. SECURITY CLASS. (of this report) UNCLASSIFIED
		15a. DECLASSIFICATION/DOWNGRADING SCHEDULE
16. DISTRIBUTION STATEMENT (of this Report) Unlimited		
17. DISTRIBUTION STATEMENT (of the abstract entered in Block 20, if different from Report)		
18. SUPPLEMENTARY NOTES		
19. KEY WORDS (Continue on reverse side if necessary and identify by block number) Wind dependence Underwater ambient noise Sea-air boundary Shipping noise		
20. ABSTRACT (Continue on reverse side if necessary and identify by block number) A study of the wind dependence of underwater ambient noise is presented. This study includes a general theory of noise generation, status of available theories, and some recent noise measurements. The general theory indicates that the stresses and the motion of sea-air boundary contribute to the major sources of wind-induced noise, and that the boundary conditions play important roles of underwater noise. Though several theories have been developed in recent years to investigate specific mechanisms of wind-induced		

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underwater noise, careful evaluations of the theories are suggested. The wind dependence of underwater ambient noise can be identified in the frequency range 1-500 Hz (and higher) from available data. Due to possible interferences of shipping noise, system noise, and flow turbulence near the hydrophone, additional field measurements are necessary to obtain quantitative assessments of wind-induced noise in the frequency range 1-100 Hz. Recommendations are given for the future research works of wind-induced noise.

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